Influence of an intensive UV preionization on evolution and EUV-emission of the laser plasma with Xe gas target (S12)

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Main ideas of the experiment proposed

The preionization of Xe gas jet target by means of the UV KrF excimer laser (λ = 248 nm) pulse applied before the main pulse of a normal IR Nd:YAG laser (λ = 1064 nm) had been proposed at our Workshop two years ago, in 2011 (oral presentation S25).

When the Nd:YAG laser is used alone, the spark begins from the 11-photon photoionization ($E_{i,\,Xe} / h\nu$ = 12.1eV / 1.16eV = 10.4). This is a highly improbable process – only several single photo-electrons can be generated in the focal volume.

As the result, subsequent collisional electron heating and collisional ionization up to Z = +1 take a rather long time.

Features of the UV KrF excimer laser spark

1. Multiphoton ionization of neutral atoms:

   $h\nu$ = 5 eV implies 3-photon ionization.

   Since there exists a group of excitation levels around E_{ex} = 10 eV ≈ $2h\nu$, the whole process, in fact, occures with 2-photon rate: 2+1-photon ionization.

   At the laser light intensity $I \approx 300$ MW/cm^2 all present atoms have to be ionized during several first nanoseconds of the KrF laser pulse.

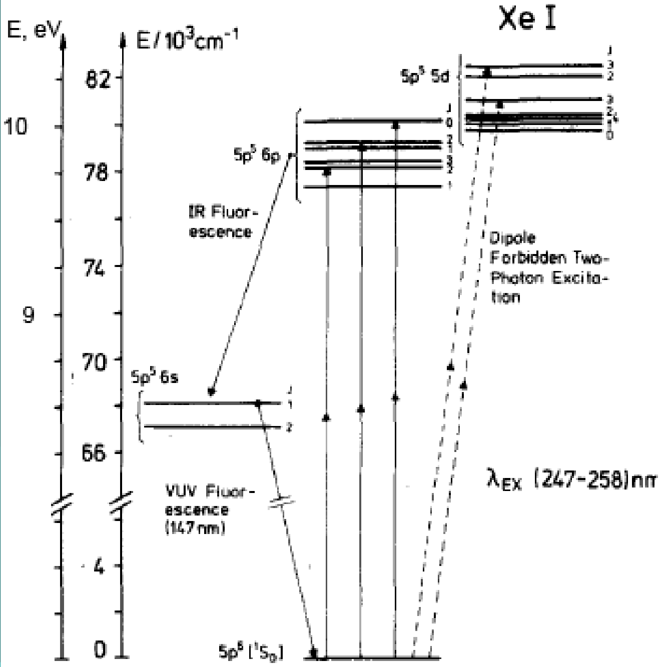


FIG. 1. Selected part of the Xe I level scheme, showing the two-photon transitions discussed in this paper. The fluorescence channels, used for detection, are indicated.

W. Gornik, S. Kindt, E. Matthias, and D. Schmidt

J. Chem. Phys., Vol. 75, No. 1, 1 July 1981

2. Subsequent collisional laser energy absorption and electron heating

$$I_{abs} \sim I_0 \, n_i^2 \, \lambda_{las}^2$$

More than 4-fold difference in wavelengths makes the UV KrF laser 18 times less effective than the Nd:YAG one, other factors being equal.

In addition, if a typical difference in the intensities between the two lasers is taken into account, plasma heating with the KrF laser turns out to be 50-70 times weaker.

3. Characteristics of the plasma produced by the KrF laser pulse:

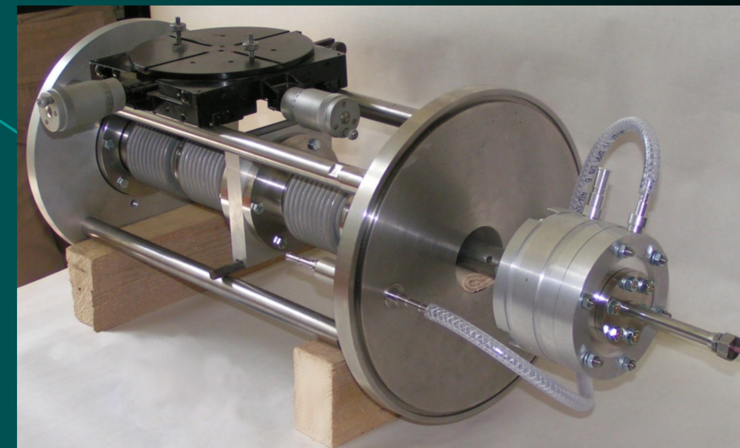
fully ionized up to $Z = +1$;

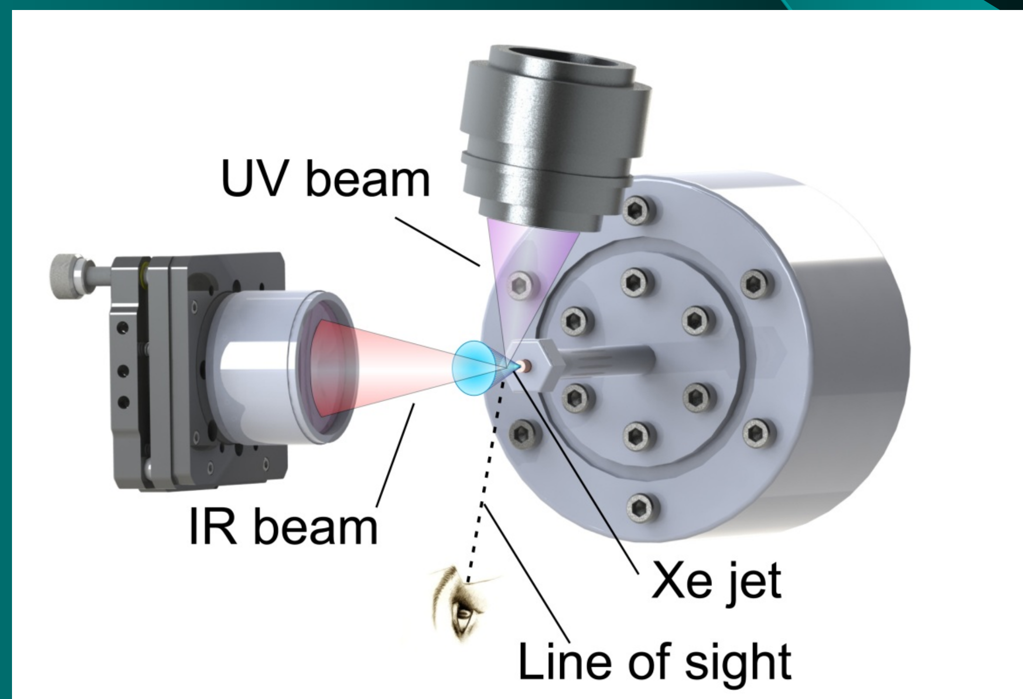
typical for the photoionization low electron energies, less than $h\nu = 5$ eV;

long recombination times – from several hundreds of nanoseconds to several microseconds;

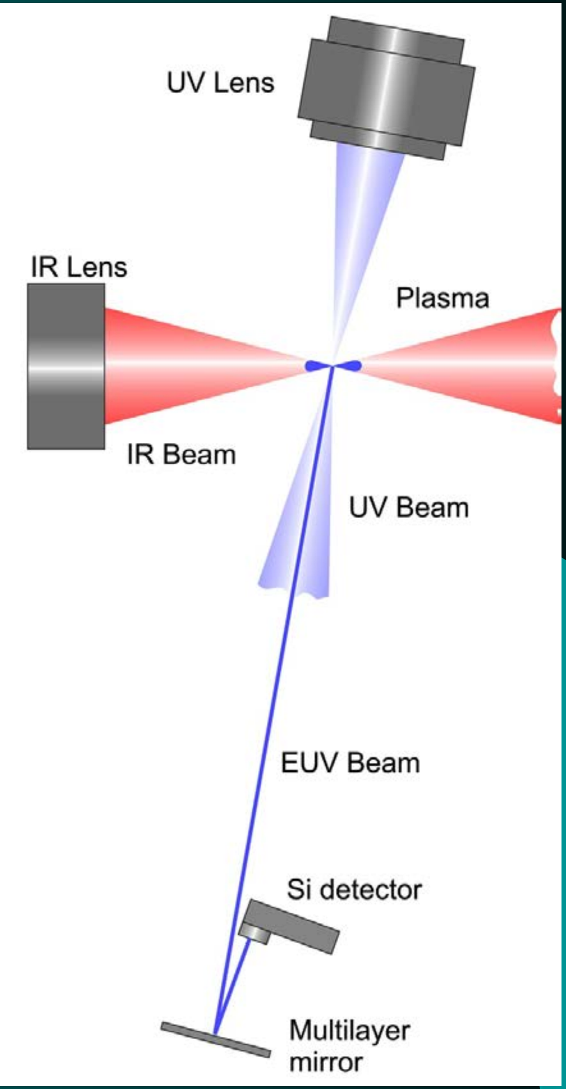
very weak emission even in the visible (the only bright and observable phase is the 2-photon excitation).

Description of the experiment





EUV detector arrangement



Detector solid angle – 3×10^{-6} rad,
time resolution is 2-3 ns

Laval nozzle

Material – alumina ceramics;

critical section diam.	0.2 mm ;
outlet diameter	1.1 mm ;
expansion coeff.	30.25 ;
length	13 mm.

An important point: in all our experiments undertaken by now, both laser foci are targeted with accuracy of 20-40 μm on the same point located on the jet axis.

Laser characteristics

Nd:YAG laser

$\lambda = 1064$ nm

E total = 1.2-1.4 J

E at plasma ≈ 0.75 J

full pulse time ≈ 30 ns

diameter at focus ≈ 50 μm

intens. at focus ≈ 1.3 TW/cm^2

KrF excimer laser

$\lambda = 248$ nm

E total ≈ 0.45 J

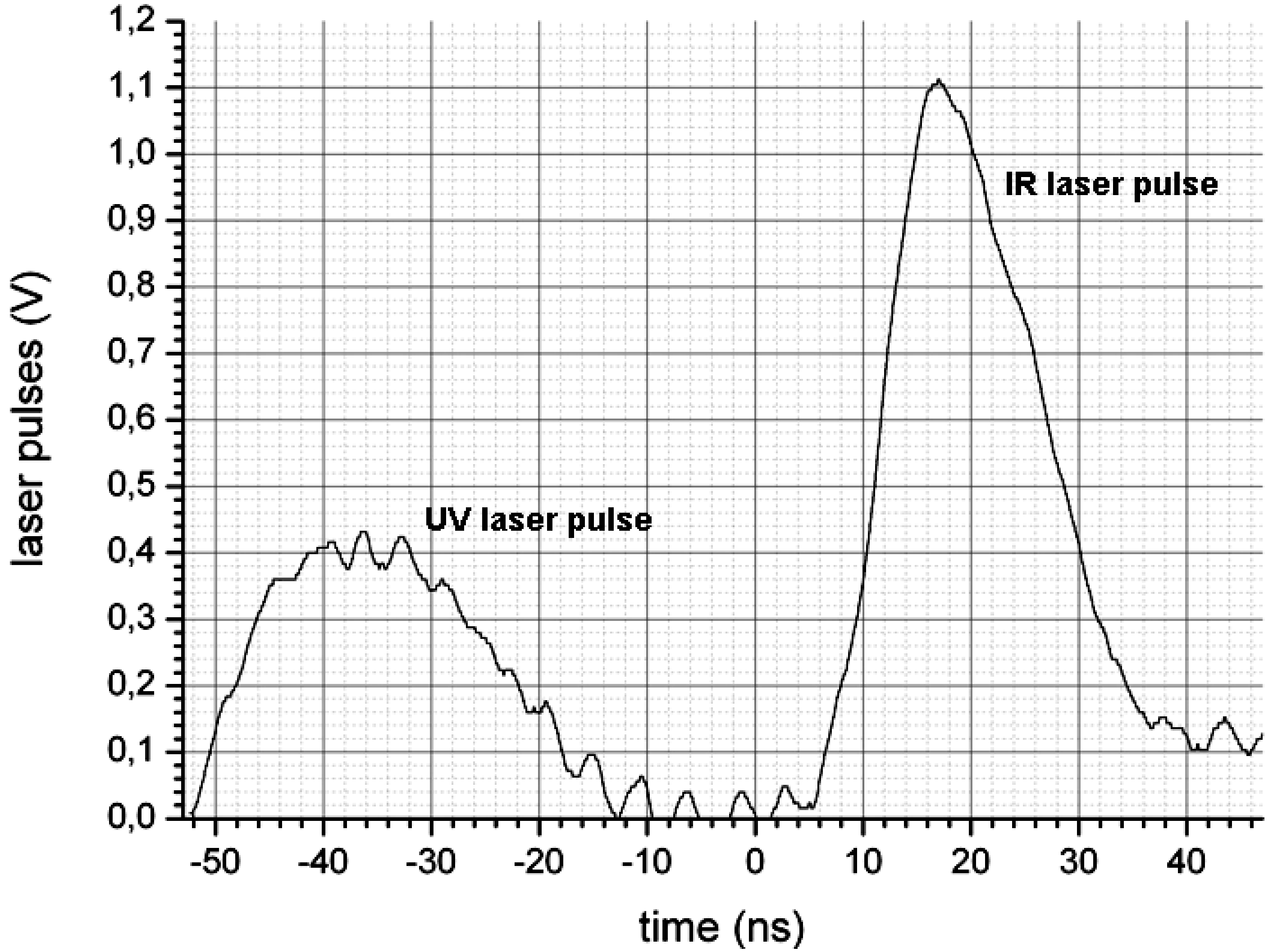
E at plasma ≈ 0.27 J

full pulse time ≈ 40 ns

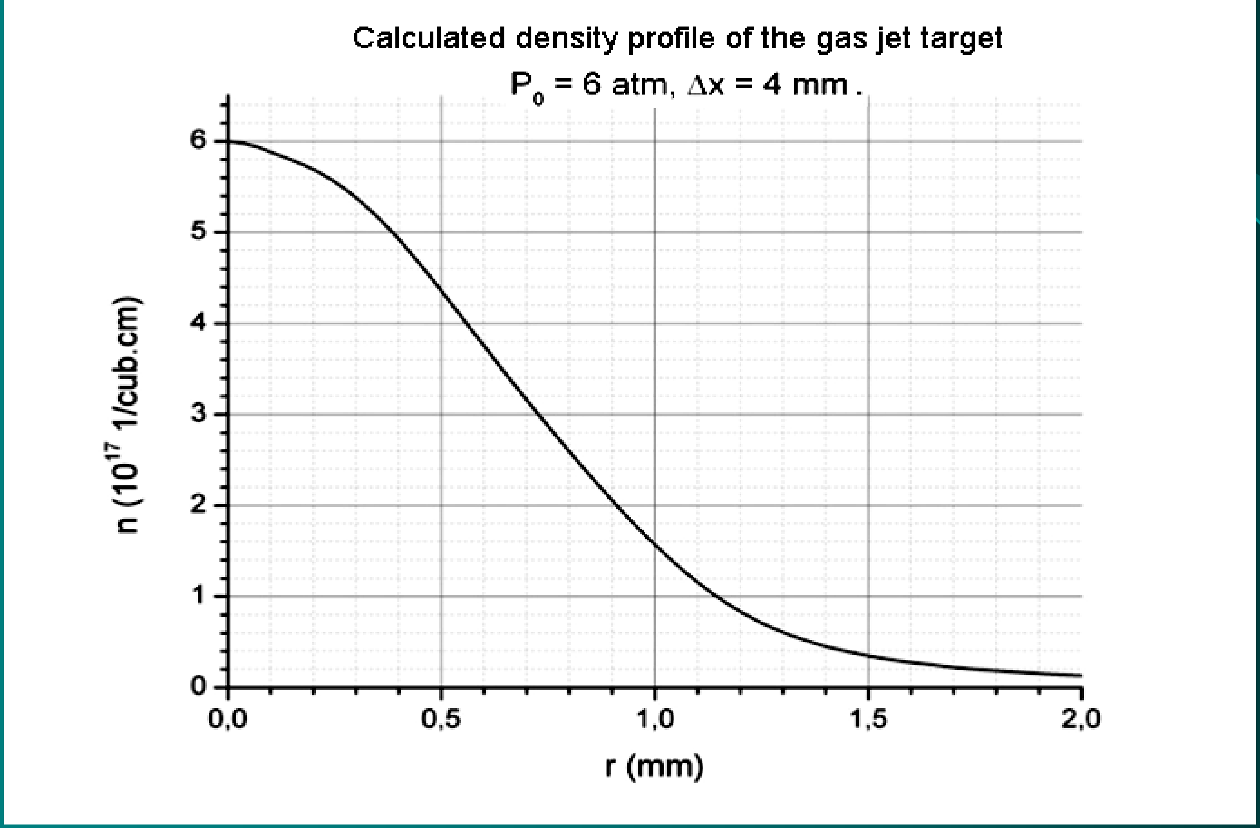
focal spot ≈ 30×80 μm^2

intens. at focus ≈ 0.3 TW/cm^2

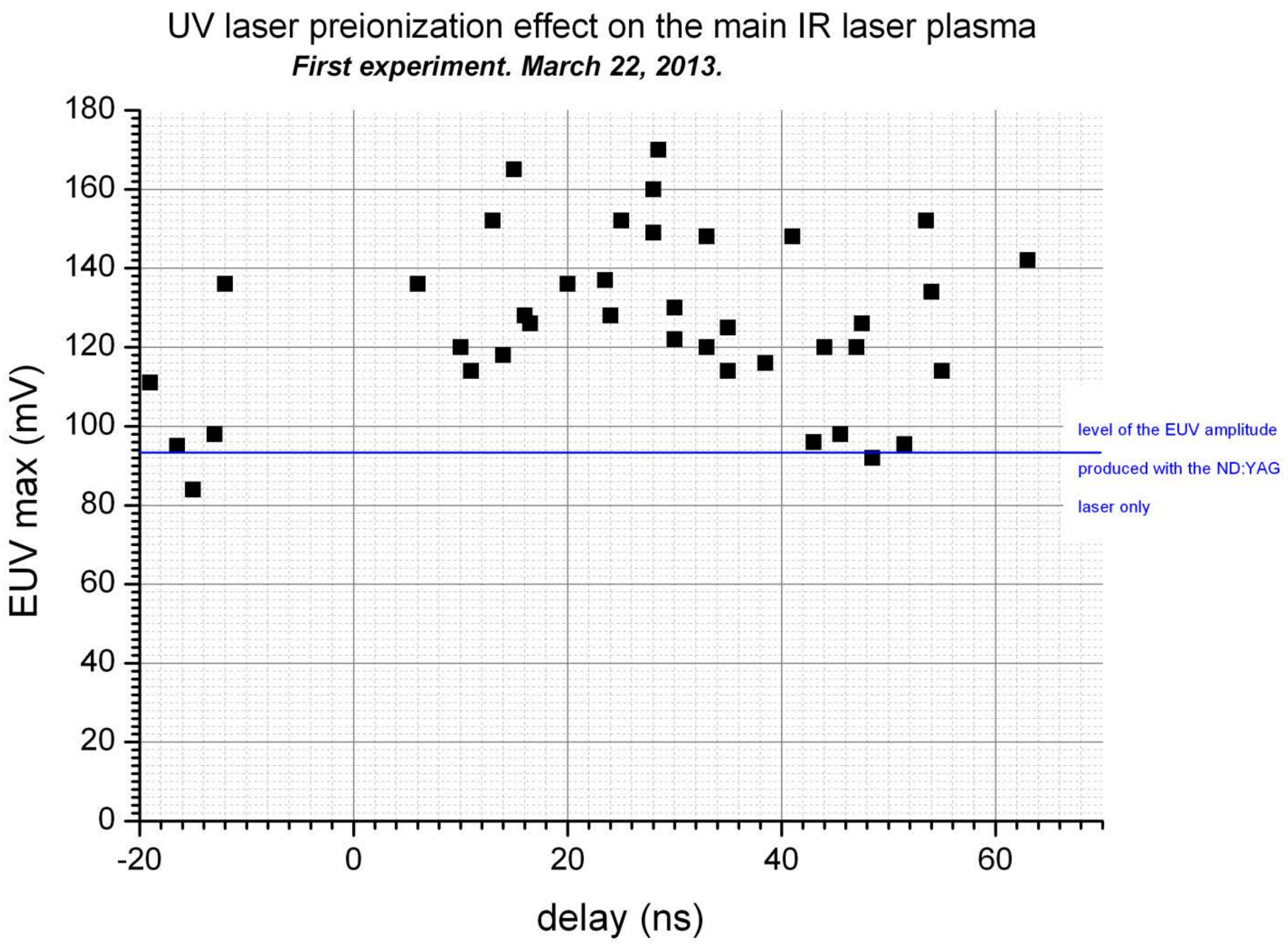
Main IR pulse preceded with the UV one (the time delay is about 60 ns)



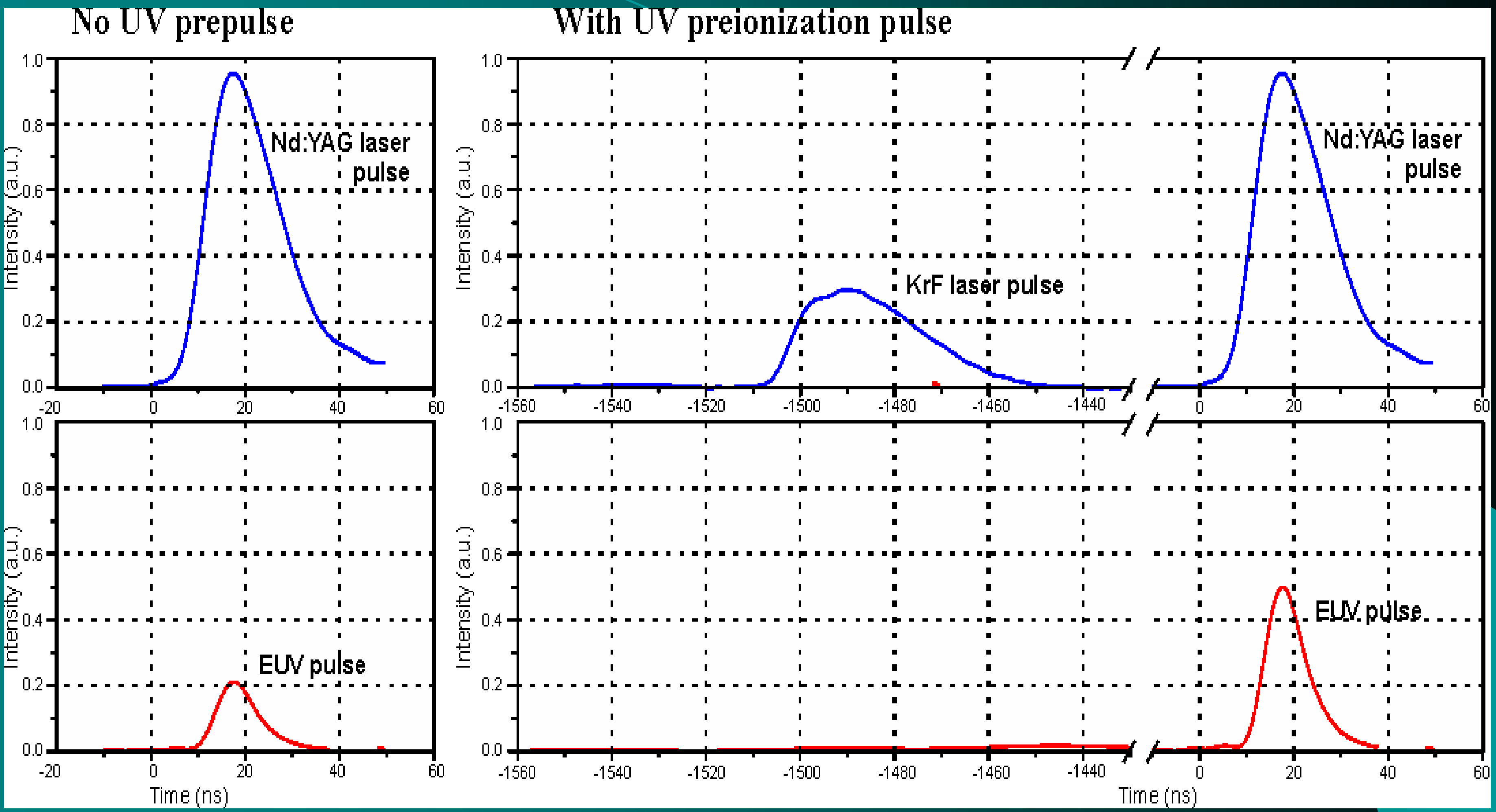
The 1st group of experiments was carried out at relatively low atomic densities of the target, n = (1-6)×10^{17} atoms/cub.cm (P_0 = 6 atm, Δx = 4 mm):

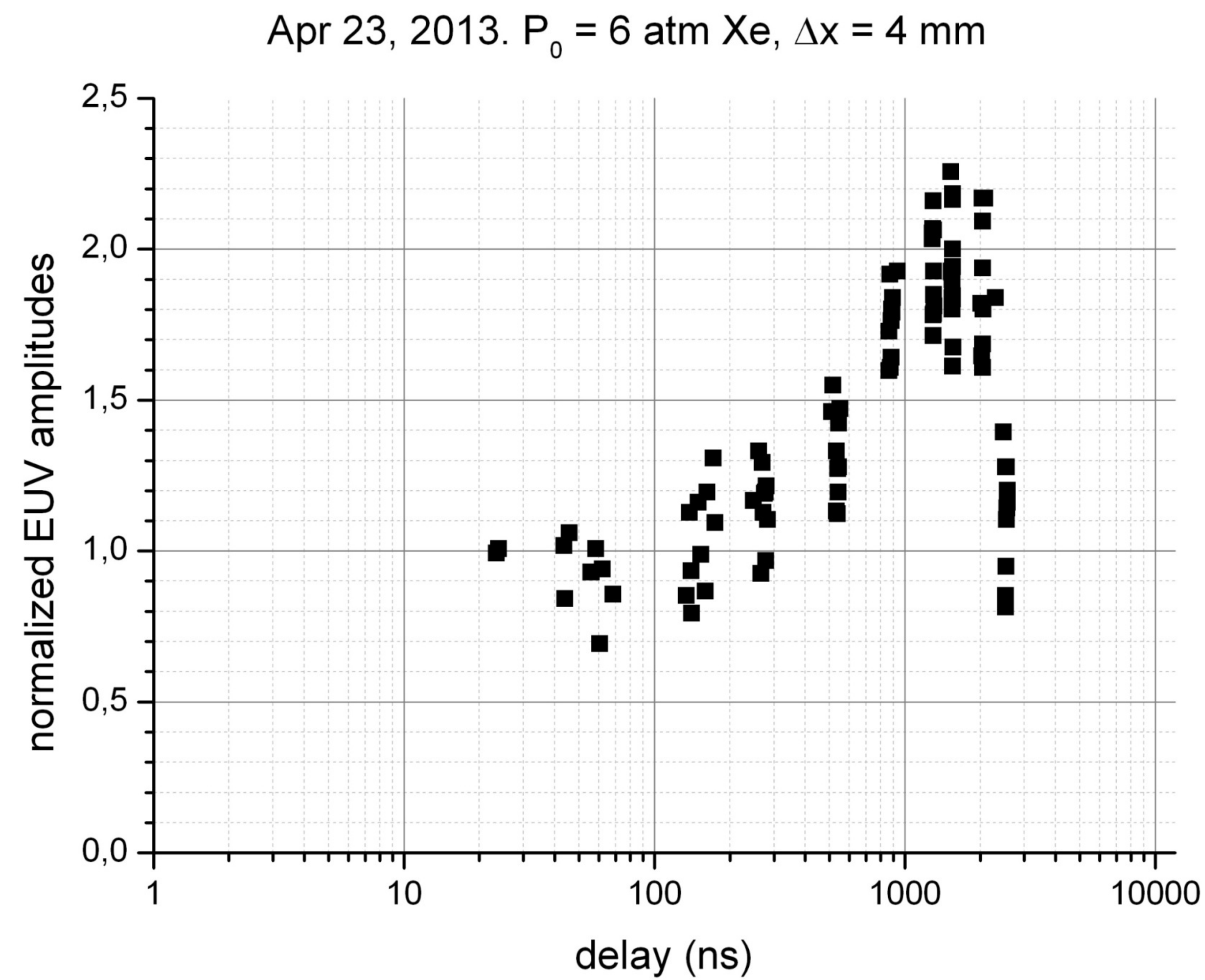


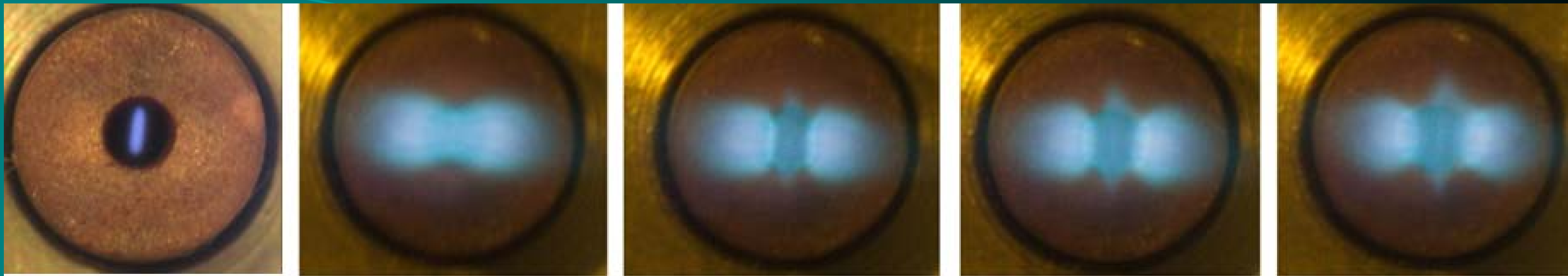
Conditions in the jet:
gas temperature is 7 to 25 °K;
axial gas speed – about 300 m/s;
radial gas flow speed – tens of m/s.



UV laser preionization effect on the main IR laser plasma
First experiment. March 22, 2013.
EUV max (mV)
delay (ns)
180
160
140
120
100
80
60
40
20
0
-20
0
20
40
60
level of the EUV amplitude
produced with the ND:YAG
laser only

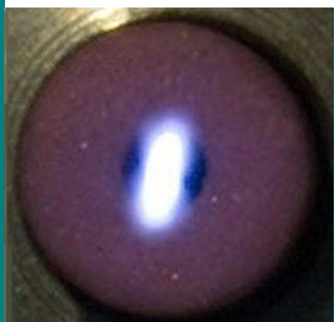

No UV prepulse
With UV preionization pulse
Nd:YAG laser pulse
KrF laser pulse
EUV pulse
Intensity (a.u.)
Time (ns)

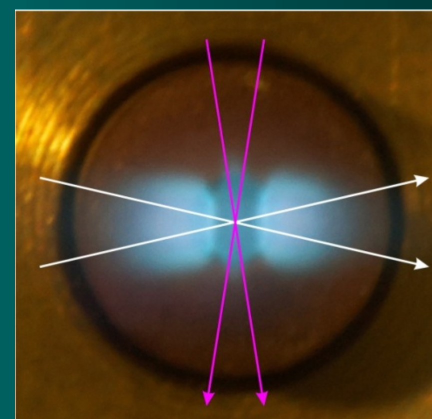

Apr 23, 2013. P_0 = 6 atm Xe, Δx = 4 mm
normalized EUV amplitudes
0,0
0,5
1,0
1,5
2,0
2,5
delay (ns)
1
10
100
1000
10000



UV prepulse alone — Main IR pulse alone — delay = 250 ns — delay = 550 ns — delay = 1050 ns

Two-pulse plasma generation

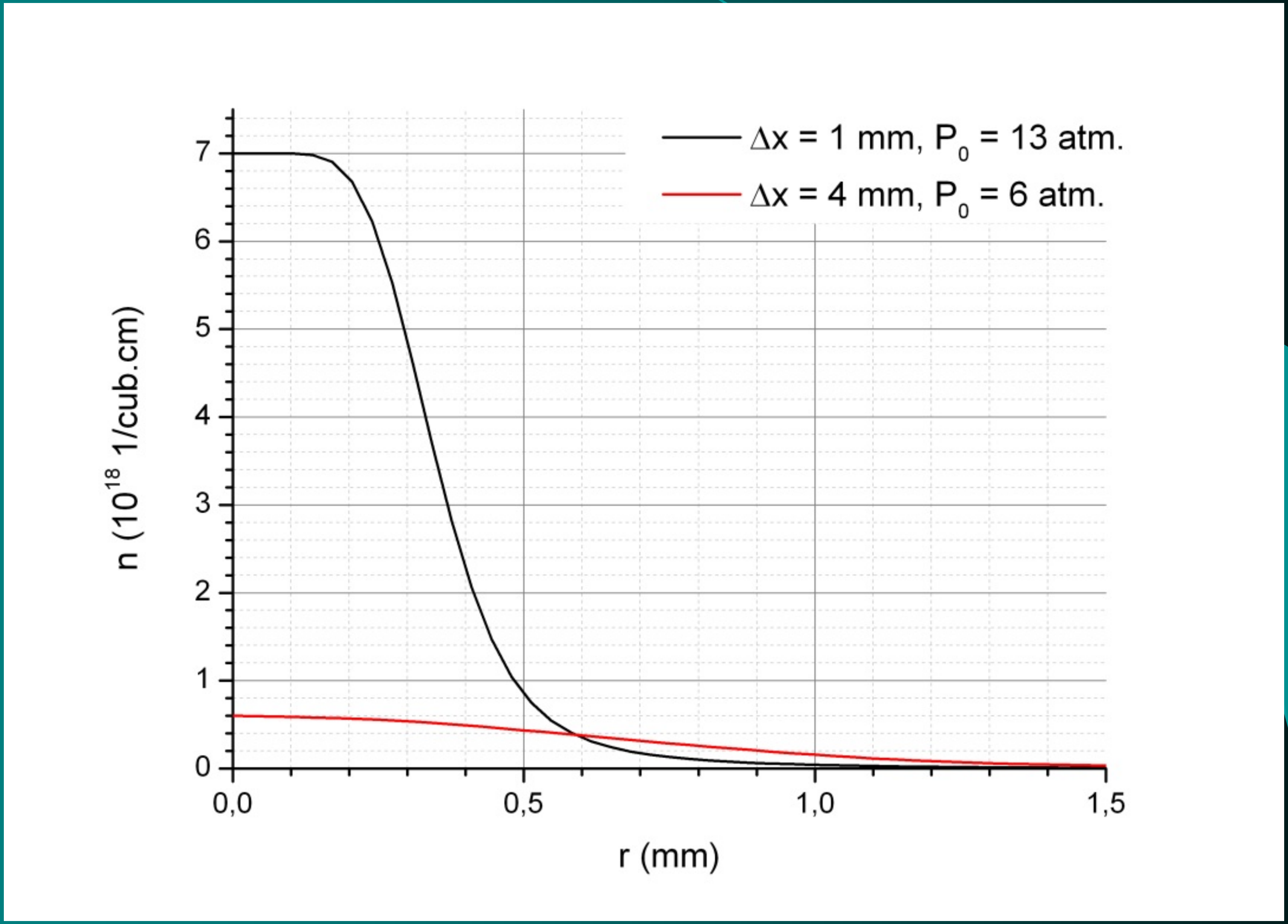




Laser beam contours

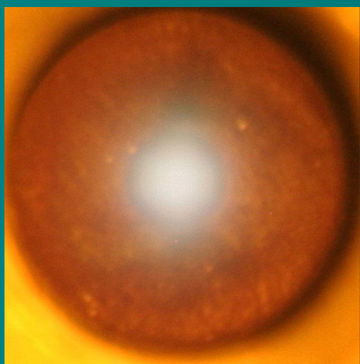
Some details on images of two-pulse plasmas suggest <u>an idea of a wave in the target</u> generated by the prepulse, expanding outwards and invisible until the IR pulse is switched on.

The 2nd group of experiments have been performed on the much denser jet, n = (0.1-7)×10^{18} cm^{-3} (P_0 = 13 atm, Δx = 1 mm), and closer to the nozzle face:



Plasma forms in the 2nd group of the experiments differ dramatically from those at the lower density.

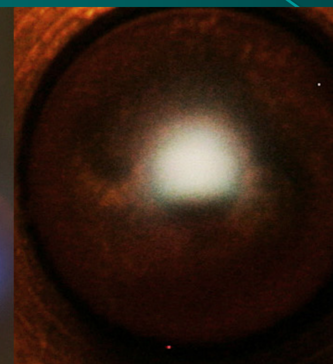
Plasmas centered on the jet axis



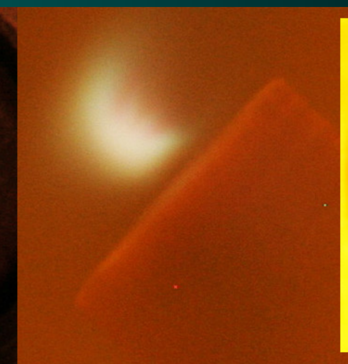
Front view

Halfside (45°) view

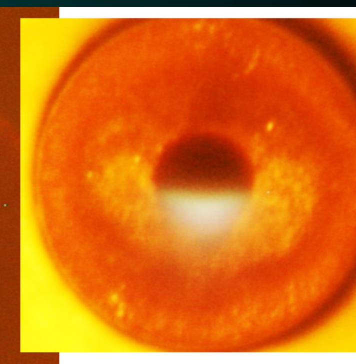
Plasmas “Gone with the Wind”



Above the axis



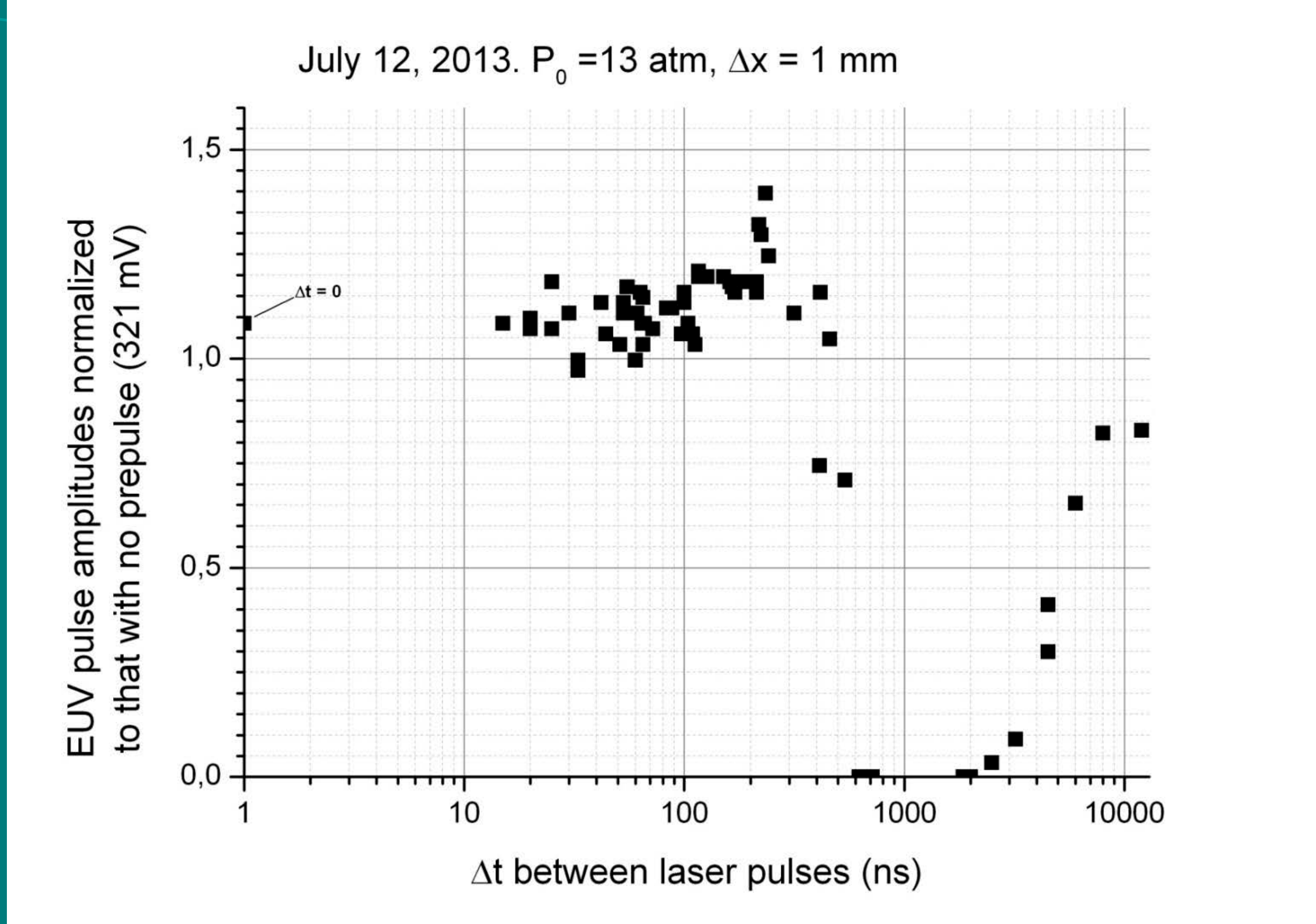
Halfside view: plasma drift due to the radial flow

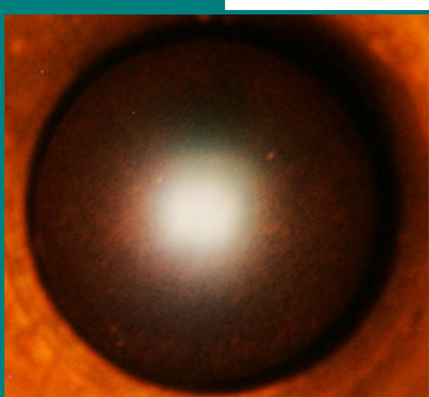


Below the axis

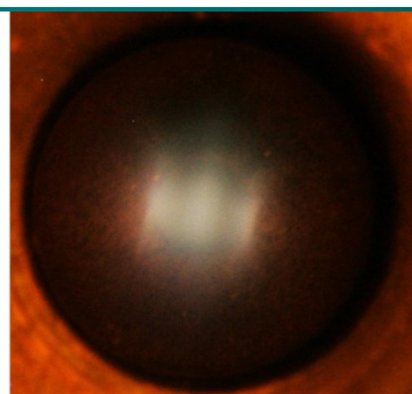
Two influences of the gas jet on the plasma form are detected here:

1) Plasma diameter is restricted by the narrow gas jet within the outlet one;
2) The radial plasma flow with speed up to 80 m/s strongly effects on non-centered plasmas.

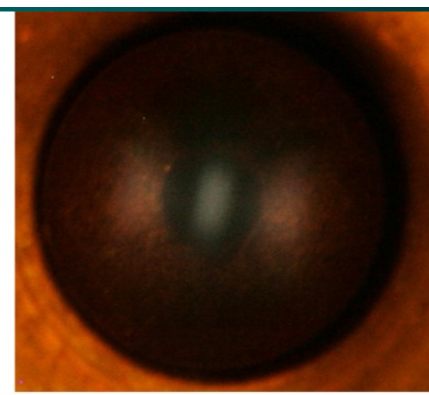




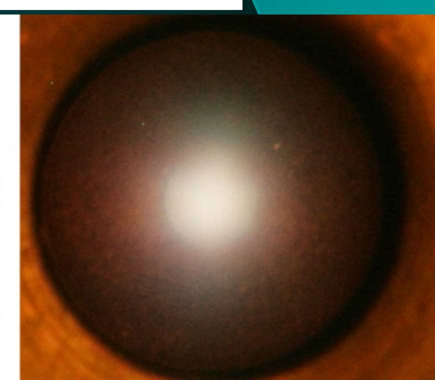
delay = 60 ns



delay = 234 ns



delay = 624 ns



delay = 8000 ns

<u>Explanations</u>

Possible preionization effects are, apparently, insufficient to explain the observed evolution of the EUV emission, with exception, probably, of time delays within several tens of nanoseconds.

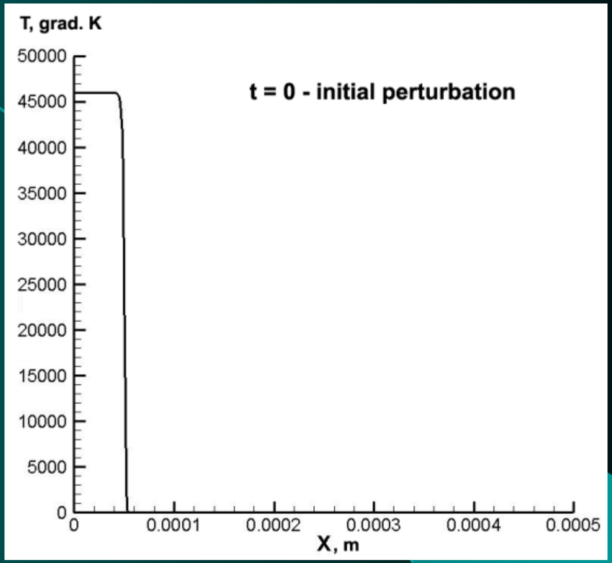
Density waves in the target generated by the prepulse

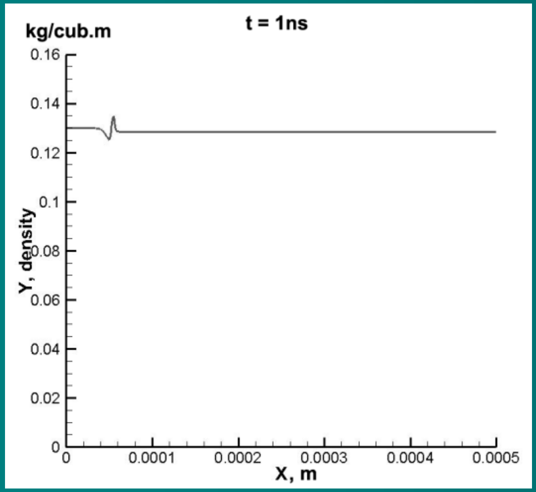
are proposed as a mechanism able to influence strongly on both the EUV emission from the plasma and the absorption along the line of sight.

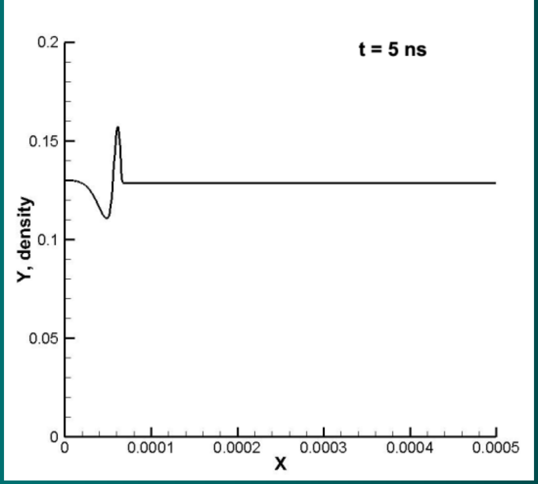
The preionization plasma, cold and low ionized, is, nevertheles, <u>a strong temperature perturbation</u> (several electronvolts) of the jet gas with its temperature of 10-20ºK. It must produce <u>a strong shock wave</u>.

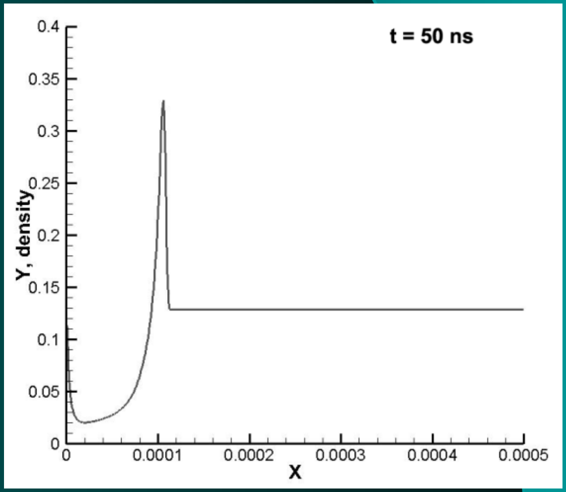
Numerical simulation of the shock wave

The 1st model: a spherically symmetric initial temperature perturbation (T = 4 eV , Ø = 100 μm) in uniform stationary Xe gas (n = 6×10^{17} cm^{-3}, as in the 1st group of experiments).

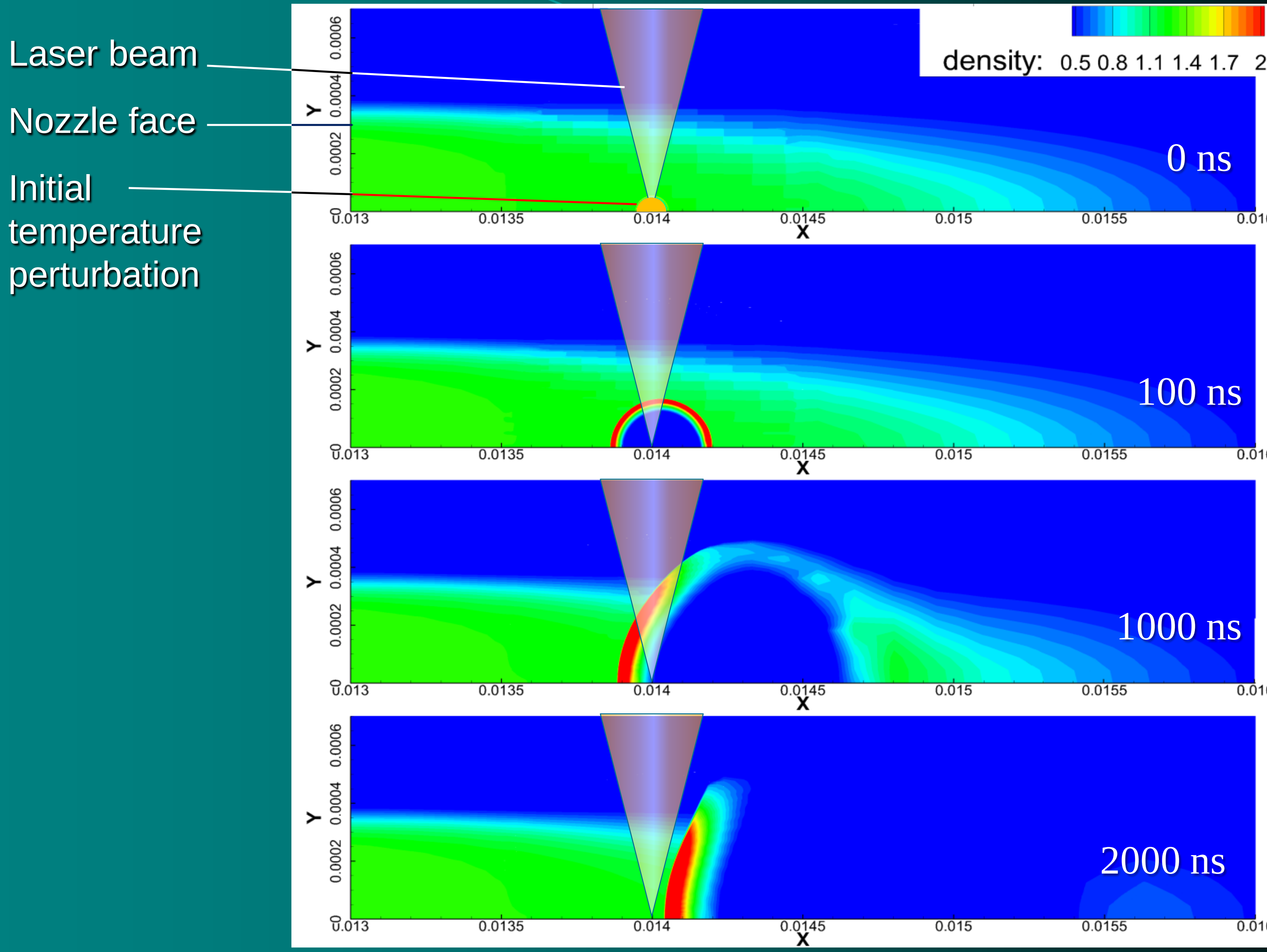


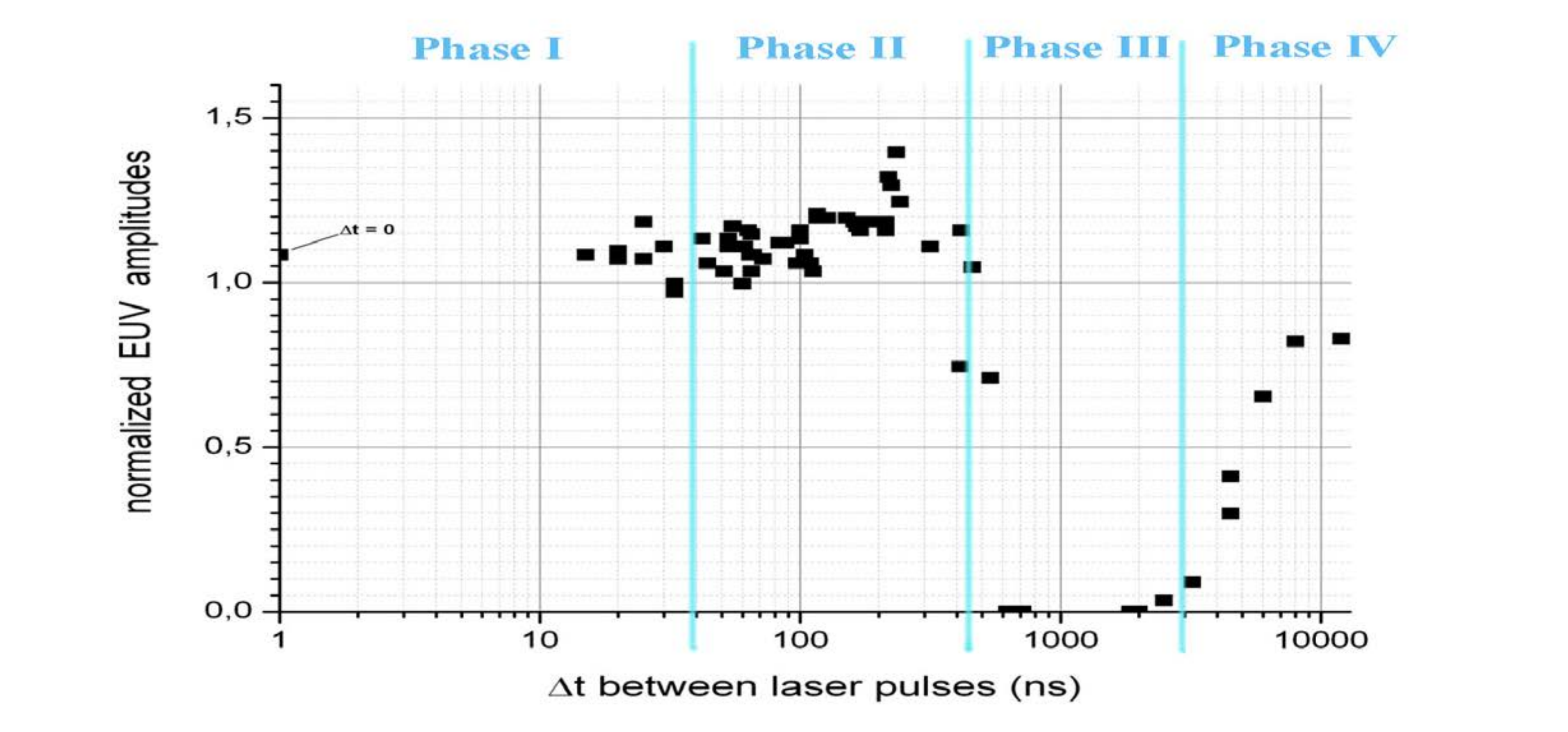






The 2nd model: the initial temperature perturbation (T = 10 eV, $\varnothing$ = 100 μm) is now placed on axis of a gas jet similar to that used in the 2nd group of experiments.





Phase I. First tens of nanoseconds – the density is not yet modified at the focus, the preionization is the only that facilitates plasma development and heating.

Phase II. An empty cavity inside the shock wave front (and around the focus) has arisen. Dense fragments on the front surface irradiated with the IR laser beam emit the EUV. The EUV output is governed by the emission/absorption balance. In the experiment with the lower jet density, the EUV enhancement reached 2.5 times.

Phase III. The shock wave cavity grows and breaks the jet. No gas is on the laser beam path, and no EUV emission.

Phase IV. Back front reminder drifts downstream, the focus falls into the non-perturbed part of the jet and the EUV emission recovers (probably, an EUV peak should be observed when the dense front reminder is crossing the focal area).

Our predecessors:

Enhancement of laser plasma extreme ultraviolet emission by shockwave-laser interaction. R. de Bruijn, K. Koshelev, S. Zakharov, V. Novikov, F. Bijkerk. Phys. Plasmas 12, 042701 (2005).

(Also R. de Bruijn, K. Koshelev, F. Bijkerk. J. Phys. D: Appl. Phys. **36** (2003) L88–L91).

Conclusion

1. The preionization effect turned out to be relatively weak (10-50%), but the gas dynamic phenomena – development and motion of the shock wave – influence dramatically on the gas jet target.
2. Therefore, two different lasers seem to be not obligatory. Two pulse operating mode of the only IR laser can be used to generate the shock wave before the main pulse.
3. A careful choice of the experimental conditions (time delay between the pulses, positions of the foci relative to each other and to the jet, line of sight direction, gas target density range) can result in 2-fold EUV radiation increase and, probably, more.

Further plans

I Continuing optimum search.

II Streak camera photography to study time sequence of the phenomena observed.

III Numerical simulation of gas dynamics phenomena in the target.

IV Time-resolved measurements of laser light absorption in the plasma.

V Absolutely calibrated measurements of the EUV output.